TITLE OF INVENTION

"PRODUCING AUTOMATIC "PAINTING" EFFECTS IN IMAGES"

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INVENTOR:

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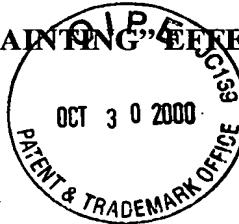
CROSS REFERENCES TO RELATED APPLICATIONS

The following Australian provisional patent applications are hereby incorporated by cross-reference. For the purposes of location and identification, US patent applications identified by their US patent application serial numbers (USSN) are listed alongside the Australian applications from which the US patent applications claim the right of priority.

CROSS-REFERENCED AUSTRALIAN PROVISIONAL PATENT NO.	US PATENT APPLICATION (CLAIMING RIGHT OF PRIORITY FROM AUSTRALIAN PROVISIONAL APPLICATION)	DOCKET NO.
PO7991	09/113,060	ART01
PO8505	09/113,070	ART02
PO7988	09/113,073	ART03
PO9395	09/112,748	ART04
PO8017	09/112,747	ART06
PO8014	09/112,776	ART07
PO8025	09/112,750	ART08
PO8032	09/112,746	ART09
PO7999	09/112,743	ART10
PO7998	09/112,742	ART11
PO8031	09/112,741	ART12
PO8030	09/112,740	ART13
PO7997	09/112,739	ART15
PO7979	09/113,053	ART16
PO8015	09/112,738	ART17
PO7978	09/113,067	ART18
PO7982	09/113,063	ART19
PO7989	09/113,069	ART20
PO8019	09/112,744	ART21
PO7980	09/113,058	ART22
PO8018	09/112,777	ART24
PO7938	09/113,224	ART25
PO8016	09/112,804	ART26
PO8024	09/112,805	ART27
PO7940	09/113,072	ART28
PO7939	09/112,785	ART29

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CROSS-REFERENCED AUSTRALIAN PROVISIONAL PATENT NO.	US PATENT APPLICATION (CLAIMING RIGHT OF PRIORITY FROM AUSTRALIAN PROVISIONAL APPLICATION)	DOCKET NO.
PO8501	09/112,797	ART30
PO8500	09/112,796	ART31
PO7987	09/113,071	ART32
PO8022	09/112,824	ART33
PO8497	09/113,090	ART34
PO8020	09/112,823	ART38
PO8023	09/113,222	ART39
PO8504	09/112,786	ART42
PO8000	09/113,051	ART43
PO7977	09/112,782	ART44
PO7934	09/113,056	ART45
PO7990	09/113,059	ART46
PO8499	09/113,091	ART47
PO8502	09/112,753	ART48
PO7981	09/113,055	ART50
PO7986	09/113,057	ART51
PO7983	09/113,054	ART52
PO8026	09/112,752	ART53
PO8027	09/112,759	ART54
PO8028	09/112,757	ART56
PO9394	09/112,758	ART57
PO9396	09/113,107	ART58
PO9397	09/112,829	ART59
PO9398	09/112,792	ART60
PO9399	09/112,791	ART61
PO9400	09/112,790	ART62
PO9401	09/112,789	ART63
PO9402	09/112,788	ART64
PO9403	09/112,795	ART65
PO9405	09/112,749	ART66
PP0959	09/112,784	ART68
PP1397	09/112,783	ART69
PP2370	09/112,781	DOT01
PP2371	09/113,052	DOT02
PO8003	09/112,834	Fluid01
PO8005	09/113,103	Fluid02
PO9404	09/113,101	Fluid03
PO8066	09/112,751	IJ01
PO8072	09/112,787	IJ02
PO8040	09/112,802	IJ03
PO8071	09/112,803	IJ04
PO8047	09/113,097	IJ05
PO8035	09/113,099	IJ06

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CROSS-REFERENCED AUSTRALIAN PROVISIONAL PATENT No.	US PATENT APPLICATION (CLAIMING RIGHT OF PRIORITY FROM AUSTRALIAN PROVISIONAL APPLICATION)	DOCKET No.
PO8044	09/113,084	IJ07
PO8063	09/113,066	IJ08
PO8057	09/112,778	IJ09
PO8056	09/112,779	IJ10
PO8069	09/113,077	IJ11
PO8049	09/113,061	IJ12
PO8036	09/112,818	IJ13
PO8048	09/112,816	IJ14
PO8070	09/112,772	IJ15
PO8067	09/112,819	IJ16
PO8001	09/112,815	IJ17
PO8038	09/113,096	IJ18
PO8033	09/113,068	IJ19
PO8002	09/113,095	IJ20
PO8068	09/112,808	IJ21
PO8062	09/112,809	IJ22
PO8034	09/112,780	IJ23
PO8039	09/113,083	IJ24
PO8041	09/113,121	IJ25
PO8004	09/113,122	IJ26
PO8037	09/112,793	IJ27
PO8043	09/112,794	IJ28
PO8042	09/113,128	IJ29
PO8064	09/113,127	IJ30
PO9389	09/112,756	IJ31
PO9391	09/112,755	IJ32
PP0888	09/112,754	IJ33
PP0891	09/112,811	IJ34
PP0890	09/112,812	IJ35
PP0873	09/112,813	IJ36
PP0993	09/112,814	IJ37
PP0890	09/112,764	IJ38
PP1398	09/112,765	IJ39
PP2592	09/112,767	IJ40
PP2593	09/112,768	IJ41
PP3991	09/112,807	IJ42
PP3987	09/112,806	IJ43
PP3985	09/112,820	IJ44
PP3983	09/112,821	IJ45
PO7935	09/112,822	IJM01
PO7936	09/112,825	IJM02
PO7937	09/112,826	IJM03
PO8061	09/112,827	IJM04

CROSS-REFERENCED AUSTRALIAN PROVISIONAL PATENT No.	US PATENT APPLICATION (CLAIMING RIGHT OF PRIORITY FROM AUSTRALIAN PROVISIONAL APPLICATION)	DOCKET No.
PO8054	09/112,828	IJM05
PO8065	09/113,111	IJM06
PO8055	09/113,108	IJM07
PO8053	09/113,109	IJM08
PO8078	09/113,123	IJM09
PO7933	09/113,114	IJM10
PO7950	09/113,115	IJM11
PO7949	09/113,129	IJM12
PO8060	09/113,124	IJM13
PO8059	09/113,125	IJM14
PO8073	09/113,126	IJM15
PO8076	09/113,119	IJM16
PO8075	09/113,120	IJM17
PO8079	09/113,221	IJM18
PO8050	09/113,116	IJM19
PO8052	09/113,118	IJM20
PO7948	09/113,117	IJM21
PO7951	09/113,113	IJM22
PO8074	09/113,130	IJM23
PO7941	09/113,110	IJM24
PO8077	09/113,112	IJM25
PO8058	09/113,087	IJM26
PO8051	09/113,074	IJM27
PO8045	09/113,089	IJM28
PO7952	09/113,088	IJM29
PO8046	09/112,771	IJM30
PO9390	09/112,769	IJM31
PO9392	09/112,770	IJM32
PP0889	09/112,798	IJM35
PP0887	09/112,801	IJM36
PP0882	09/112,800	IJM37
PP0874	09/112,799	IJM38
PP1396	09/113,098	IJM39
PP3989	09/112,833	IJM40
PP2591	09/112,832	IJM41
PP3990	09/112,831	IJM42
PP3986	09/112,830	IJM43
PP3984	09/112,836	IJM44
PP3982	09/112,835	IJM45
PP0895	09/113,102	IR01
PP0870	09/113,106	IR02
PP0869	09/113,105	IR04
PP0887	09/113,104	IR05

CROSS-REFERENCED AUSTRALIAN PROVISIONAL PATENT NO.	US PATENT APPLICATION (CLAIMING RIGHT OF PRIORITY FROM AUSTRALIAN PROVISIONAL APPLICATION)	DOCKET NO.
PP0885	09/112,810	IR06
PP0884	09/112,766	IR10
PP0886	09/113,085	IR12
PP0871	09/113,086	IR13
PP0876	09/113,094	IR14
PP0877	09/112,760	IR16
PP0878	09/112,773	IR17
PP0879	09/112,774	IR18
PP0883	09/112,775	IR19
PP0880	09/112,745	IR20
PP0881	09/113,092	IR21
PO8006	09/113,100	MEMS02
PO8007	09/113,093	MEMS03
PO8008	09/113,062	MEMS04
PO8010	09/113,064	MEMS05
PO8011	09/113,082	MEMS06
PO7947	09/113,081	MEMS07
PO7944	09/113,080	MEMS09
PO7946	09/113,079	MEMS10
PO9393	09/113,065	MEMS11
PP0875	09/113,078	MEMS12
PP0894	09/113,075	MEMS13

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

Not applicable.

FIELD OF THE INVENTION

The present invention relates to an image processing method and apparatus and, in particular, discloses producing automatic painting effects in images.

The present invention further relates to the field of image processing and in particular to producing artistic effects in images.

BACKGROUND OF THE INVENTION

Recently, it has become quite popular to provide filters which produce effects on images similar to popular artistic painting styles. These filters are designed to take an image and produce a resultant secondary image which appears to be an artistic rendition of the primary image in one of the artistic

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styles.

One extremely popular artist in modern times was Vincent van Gogh. It is a characteristic of art works produced by this artist that the direction of brush strokes in flat areas of his paintings strongly follow the direction of edges of dominant features in the painting. For example, his works entitled "Road with Cypress and Star", "Starry Night" and "Portrait of Doctor Gachet" are illustrative examples of this process.

It would be desirable to provide a computer algorithm which can automatically produce a "van Gogh" effect on an arbitrary input image.

SUMMARY OF THE INVENTION

It is an object of the present invention to produce automatic "van Gogh" type effects in images.

In accordance with the first aspect of the present invention there is provided a method of automatically processing an image comprising locating within the image features having a high spatial variance and stroking the image with a series of brush strokes emanating from those areas having high spatial variance.

Preferably, the brush strokes have decreasing sizes near important features of the image.

Additionally, the position of a predetermined portion of brush strokes can undergo random jittering.

BRIEF DESCRIPTION OF THE DRAWINGS

Notwithstanding any other forms which may fall within the scope of the present invention, preferred forms of the invention will now be described, by way of example only, with reference to the accompanying drawings which:

Fig. 1 illustrates the major steps in the preferred embodiment;

Fig. 2 illustrates the Sobel filter co-efficients utilised within the preferred embodiment;

Figs. 3 & 4 illustrate the process of offsetting curves utilised in the preferred embodiments.

DESCRIPTION OF PREFERRED AND OTHER EMBODIMENTS

The preferred embodiment is preferable implemented through suitable programming of a hand held camera device such as that described in Australian Provisional Patent Application entitled "Image Processing Method and Apparatus (ART01)" filed concurrently herewith by the present applicant the content of which is hereby specifically incorporated by cross reference.

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The aforementioned patent specification discloses a camera system, hereinafter known as an "Artcam" type camera, wherein sensed images can be directly printed out by an Artcam portable camera unit. Further, the aforementioned specification discloses means and methods for performing various manipulations on images captured by the camera sensing device leading to the production of various effects in any output image. The manipulations are disclosed to be highly flexible in nature and can be implemented through the insertion into the Artcam of cards having encoded thereon various instructions for the manipulation of images, the cards hereinafter being known as Artcards. The Artcam further has significant onboard processing power by an Artcam Central Processor unit (ACP) which is interconnected to a memory device for the storage of important data and images.

In the preferred embodiment there is described an algorithm which will automatically convert a photographic image into a "painted" rendition of that image which replaces groups of pixels in the input image with "brush strokes" in the output image. The algorithm works by automatically detecting dominant edges and propagating the edge direction information into flat areas of the image so that brush strokes can be oriented in such a way as to approximate the van Gogh style. The algorithm is suitable for implementation on the aforementioned Artcam device.

Turning initially to Fig. 1, the algorithm comprises a number of steps 1. These steps include an initial step of filtering the image to detect its edges 2. Next, the edges are thresholded or "skeletonised" 4 before being processed 5 to determine the final edges 6. Bézier curves are then fitted to the edges. Next, the curves are offset 7 and brush strokes are placed on final image 8. The process 7 and 8 is iterated until such time as the image is substantially covered by brush strokes. Subsequently, final "touching up" 9 of the image is performed.

Turning now to describe each step in more detail. In the first step 2 of filtering to detect edges, a Sobel 3 x 3 filter having co-efficient sets 12 and 13 as illustrated in Fig. 2 can be applied to the image. The Sobel filter is a well known filter utilised in digital image processing and its properties are fully discussed in the standard text "Digital Image Processing" by Gonzalez and Woods published 1992 by the Addison - Wesley publishing company of Reading, Massachusetts at pages 197-201. The Sobel derivative filter can be applied by either converting the image to greyscale before filtering or filtering each of the colour channels of an image separately and taking the maximum. The result of Sobel filtering is the production of a greyscale image indicating the per-pixel edge strength of the image.

Next, the resultant per-pixel edge strength image is thresholded 3 so as to produce a corresponding thresholded binary image. The threshold value can be varied however, a value of 50%

of the maximum intensity value is suitable. For each pixel in the edge strength image the pixel is compared with the threshold and if it is greater than the threshold a "one" is output and if it is less than the threshold a "zero" is output. The result of this process is to produce a threshold edge map.

Next, the thresholded edge map is "skeletonised" at step 4 of Fig. 1. The process for skeletonising an image is fully set out in the aforementioned reference text at pages 491-494 and in other standard texts. The process of skeletonisation produces a "thinned" skeletonised edge map maintaining a substantial number of characteristics of the thresholded edge map.

In a next step the edges of the skeletonised edge map are determined to yield a data structure which comprises a list of further lists of points within the image. Preferably, only edges having a length greater than a predetermined minimum are retained in the list.

As the skeletonised image contains only single-pixel-width edges, possibly with multiple branches, the following algorithm expressed as a C++ code fragment sets out one method of determining or identifying the points which belong to each contiguous edge in the skeletonised image. It breaks branching edges into separate edges, and chooses to continue along the edge in the direction which minimises the curvature of each branch - ie. at a branch-point it favours following the branch which induces the least curvature. The code is as follows:

```
void

FollowEdges

(

        Image& image,

        int minimumEdgeLength,

        PointListList& pointListList

)

(

        pointListList.Erase();

        for (int row = 0; row < image.Height(); row++)

        {

                for (int col = 0; col < image.Width(); col++)

                {

                        If (image[row][col] > 0)

                        {

                                PointList pointList;
```

```
                    // append the starting point to the point list,

                    // and clear it so we don't find it again

                    pointList.Append(Point(col, row));

                    image[row][col] = 0;


                    // follow the edge from the starting point to its beginning

                    FollowEdge(row, col, image, pointList);


                    // reverse the order of the points accumulated so far,

                    // and follow the edge from the starting point to its end

                    pointList.Reverse();

                    FollowEdge(row, col, image, pointList);


                    // keep the point list only if it's long enough

                    if (pointList.Size() >= minimumEdgeLength)

                    pointListList.Append(pointList);

                }

            }

        }

}


// table of row and column offsets to eight surrounding neighbours

// (indexed anti-clockwise, starting east)

static int offsetTable[8][2] =

{

    {0, 1}, {-1, 1}, {-1, 0}, {-1, -1}, {0, -1}, {1, -1}, {1, 0}, {1,1}

};


// table of preferred neighbour checking orders for given direction

// (indexed anti-clockwise, starting east favouring non diagnals)

static int nextDirTable[8][8] =
```

```
{
        {0,     2,      6,      1,      7,      3,      4,      5),
        {2,     0,      1,      3,      7,      4,      5,      6),
        {2,     4,      0,      3,      1,      5,      6,      7},
        {4,     2,      3,      5,      1,      6,      7,      0),
        {4,     6,      2,      5,      3,      7,      0,      1},
        {6,     4,      5,      7,      3,      0,      1,      2),
        {6,     0,      4,      7,      5,      1,      2,      3},
        {0,     6,      7,      1,      5,      2,      3,      4),
};

void
FollowEdge
(
        int row,
        int col,
        Image& image,
        PointList& pointList
)
{
        Vector edgeHistory[EDGE_HISTORY_SIZE];
        int historyIndex = 0;

        for (;;)
        {
                // table of pre-computed
                // compute tangent estimate from edge history
                Vector tangent;
                for (int i = 0; i < EDGE_HISTORY_SIZE; i++)
                        tangent += edgeHistory[i];
```

```
// determine tangent angle and quantize to eight directions
// (direction zero corresponds to the range -PI/8 to +PI/8, i.e east)
double realAngle = tangent.Angle();
int angle = (int) ((realAngle * 255) / (2 * PI) + 0.5);
        int dir = ((angle - 16 + 256) % 256) / 32;


        // try surrounding pixels, fanning out from preferred
        // (i.e. edge) direction
        int* pNextDir = nextDirTable[dir];
        bool bFound = false;


for (i = 0; i < 8; i++)
{
                // determine row and column offset for current direction
                int rowOffset = offsetTable[dir][0];
                int colOffset = offsetTable[dir][1];


                // done testing neighbours if edge pixel found


                if (image [row + rowOffset] [col + colOffset] > 0)
                {
                        // determine edge pixel address
                        Point oldPoint (col, row);
                        row += rowOffset;
                        col += colOffset;
                        Point newPoint (col, row);


                        // update edge tangent history
                        tangent = newPoint - oldPoint;
                        tangent.Normalize();
                        edgeHistory[histroyIndex] = tangent;
                        historyIndex = (historyIndex + 1) % EDGE_HISTORY_SIZE;
```

```
                          // append edge pixel to point list
                          pointList.Append(newPoint);


                          // clear edge pixel, so we don't find it again
                          image[row][col] = 0;
                          bFound = true;
                          break;
                  }
                  // determine next direction to try
                  dir = pNextDir[i];
          }


          // done following edge if no edge pixel found
          if (!bFound)
                  break;

      }
}
```

The result of utilising this algorithmic component on the skeletonised edgemap is to produce a list of edges having at least a predetermined size. A suitable size was found to be a length of 20 pixel elements.

In the next step 6 of Fig. 1, Bézier curves are fitted to each of the edge lists derived from step 5. For each list of edges, a piece wise Bézier curve is fitted to the corresponding list of points. A suitable algorithm for fitting the piece wise Bézier curve is Schneider's curve fitting algorithm as set out in Schneider, P.J., "An Algorithm for Automatically Fitting Digitised Curves", in Glassner,A.S. (Ed.), Graphics Gems, Academic Press, 1990. This algorithm provides quick convergence to a good fit which aims only for geometric continuity and not parametric continuity. Schneider's algorithm is recursive, such that if the fit is poor, is sub-divides the curve at the point of maximum error and fits the curves to the two halves separately. Next an estimate of the tangent at the split point is derived using only the two points on either side of the split point. For dense point sets, this tends to amplify the local noise. An improved quality of curve fitting can be alternatively undertaken by using points further

away from the split point as the basis for the tangent.

In the next steps 7 of Fig. 1, the curves are offset from the primary curve list by half a desired "brush stroke width". The offsetting occurring on both sides of the primary curve list with the result being two curves approximately one stroke width apart from one another which run parallel to and on either side of the original primary curve.

The following algorithm is utilized to generate a piece wise Bézier curves which are approximately parallel to a specified piece wise Bézier curves and includes the steps.

    i.   Create an empty point list.

    ii.   Create and empty tangent (vector) list.

    iii.   Evaluate selected points on each curve segment making up the piece-wise curve and offset them by the specified offset value. Append the offset points to the point list, and their corresponding tangents to the tangent list. This process is described below with reference to Fig. 2 and 3.

    iv.   Fit a piece-wise Bézier curve to the resultant point list. Rather than estimating tangents during the curve-fitting process, use the exact tangents associated with the offset points.

Offset each curve segment as follows:

    i.   Evaluate the curve value, normalised tangent and normalised normal normalised to the size of the image for a set of evenly-spaced parameter value between (and including) 0.0 and 1.0 (eg. a spacing of 0.25).

    ii.   Scale the normals by the specified offset value.

    iii.   Construct line segments using the curve points and scaled normals.

    iv.   If any two line segments intersect, eliminate the point associated with one of them.

    v.   Append the surviving points to the point list, and append their corresponding tangents to the tangent list. Only append the point associated with parameter value 1.0 if the segment in question is the last in the piece-wise curve, otherwise it will duplicate the point associated with parameter value 0.0 of the next segment.

The process of offsetting each curve segment can proceed as following:

    1.   Firstly, for a set of evenly spaced parameter values on the Bézier curve between (and including) 0.0 and 1.0, for each parameter value PN (Fig. 3) the curve value 30 a normalised tangent 31 and normalised normal 32 are calculated.

    2.   Next, the normals 32 are scaled 34 by a specified offset value.

    3.   Next a line segment from the point 30 to a point 36, which is at the end of the scaled

normal 34 is calculated.

4.   Next, the line segment 30, 36 is checked against corresponding line segments for all other points on the curve eg. 38, 39. If any two line segments intersect, one of the points 36 is discarded.

5.   The surviving points are appended to the point list and their corresponding tangents are appended to the tangent list. The point associated with the parameter value 1.0 is appended only if the segment in question is the last in the piece-wise curve segment. Otherwise, it will duplicate the point associated with the parameter value 0.0 of the next segment.

Turning to Fig. 4, the end result of the offset of curves in accordance with step 7 of Fig. 1 is to produce for a series of Bézier curve segments C1, C2 etc. Firstly, a series of parametrically spaced points, P1 - P5. Next, the normalisation points N1 - N5 are produced (corresponding through to point 36 of Fig. 3), for each of the points P1 - P5. Next, the resultant piece-wise Bézier curve segment 40 is produced by utilising the points in 1 - N5. This process is then repeated for the opposite curve comprising the points N6 - N10 and curve 41. This process is then repeated for each of the subsequent piece-wise curves C2 etc. The result is the two curves of 40, 41 being substantially parallel to one another and having a spaced apart width of approximately one brush stroke.

Next, a series of brush strokes are placed into the output image along the curves. The strokes are oriented in accordance with the curve tangent direction. Each brush stroke is defined to have a foot print which defines where it may not overlap with other brush strokes. A brush stroke may only be place along the curve if its foot print does not conflict with the foot prints already present in the output image. Any curves that do not have any brush strokes placed along them are discarded and the process of steps 7 and 8 are iterated in a slightly modified form until no curves are left. The slightly modified form of step 7 is to offset the curves by one brush stroke in the outward direction rather than the half brush stroke necessary when offsetting curves from the curve C1 of Fig. 4.

It has been found by utilisation of the above method that the result produced consists of a series of brush strokes which emanate from objects of interest within the image.

Subsequent to covering the image with brush strokes of a given size, further processing steps can be undertaken with smaller and smaller brush strokes and increasing derivative threshold levels so as to more accurately "brush stroke" important features in the image. Such a technique is similar to that used by van Gogh in certain portions of his images where details are required.

It would be appreciated by a person skilled in the art that numerous variations and/or modifications may be made to the present invention as shown in the specific embodiment without

departing from the spirit or scope of the invention as broadly described. The present embodiment is, therefore, to be considered in all respects to be illustrative and not restrictive.

Ink Jet Technologies

The embodiments of the invention use an ink jet printer type device. Of course many different devices could be used. However presently popular ink jet printing technologies are unlikely to be suitable.

The most significant problem with thermal ink jet is power consumption. This is approximately 100 times that required for high speed, and stems from the energy-inefficient means of drop ejection. This involves the rapid boiling of water to produce a vapor bubble which expels the ink. Water has a very high heat capacity, and must be superheated in thermal ink jet applications. This leads to an efficiency of around 0.02%, from electricity input to drop momentum (and increased surface area) out.

The most significant problem with piezoelectric ink jet is size and cost. Piezoelectric crystals have a very small deflection at reasonable drive voltages, and therefore require a large area for each nozzle. Also, each piezoelectric actuator must be connected to its drive circuit on a separate substrate. This is not a significant problem at the current limit of around 300 nozzles per printhead, but is a major impediment to the fabrication of pagewidth printheads with 19,200 nozzles.

Ideally, the ink jet technologies used meet the stringent requirements of in-camera digital color printing and other high quality, high speed, low cost printing applications. To meet the requirements of digital photography, new ink jet technologies have been created. The target features include:

low power (less than 10 Watts)

high resolution capability (1,600 dpi or more)

photographic quality output

low manufacturing cost

small size (pagewidth times minimum cross section)

high speed (< 2 seconds per page).

All of these features can be met or exceeded by the ink jet systems described below with differing levels of difficulty. Forty-five different ink jet technologies have been developed by the Assignee to give a wide range of choices for high volume manufacture. These technologies form part of separate applications assigned to the present Assignee as set out in the table under the heading Cross References to Related Applications.

The ink jet designs shown here are suitable for a wide range of digital printing systems, from

battery powered one-time use digital cameras, through to desktop and network printers, and through to commercial printing systems.

For ease of manufacture using standard process equipment, the printhead is designed to be a monolithic 0.5 micron CMOS chip with MEMS post processing. For color photographic applications, the printhead is 100 mm long, with a width which depends upon the ink jet type. The smallest printhead designed is IJ38, which is 0.35 mm wide, giving a chip area of 35 square mm. The printheads each contain 19,200 nozzles plus data and control circuitry.

Ink is supplied to the back of the printhead by injection molded plastic ink channels. The molding requires 50 micron features, which can be created using a lithographically micromachined insert in a standard injection molding tool. Ink flows through holes etched through the wafer to the nozzle chambers fabricated on the front surface of the wafer. The printhead is connected to the camera circuitry by tape automated bonding.

Tables of Drop-on-Demand Ink Jets

Eleven important characteristics of the fundamental operation of individual ink jet nozzles have been identified. These characteristics are largely orthogonal, and so can be elucidated as an eleven dimensional matrix. Most of the eleven axes of this matrix include entries developed by the present assignee.

The following tables form the axes of an eleven dimensional table of ink jet types.

Actuator mechanism (18 types)

Basic operation mode (7 types)

Auxiliary mechanism (8 types)

Actuator amplification or modification method (17 types)

Actuator motion (19 types)

Nozzle refill method (4 types)

Method of restricting back-flow through inlet (10 types)

Nozzle clearing method (9 types)

Nozzle plate construction (9 types)

Drop ejection direction (5 types)

Ink type (7 types)

The complete eleven dimensional table represented by these axes contains 36.9 billion possible configurations of ink jet nozzle. While not all of the possible combinations result in a viable ink jet technology, many million configurations are viable. It is clearly impractical to

elucidate all of the possible configurations. Instead, certain ink jet types have been investigated in detail. These are designated IJ01 to IJ45 above which matches the docket numbers in the table under the heading Cross References to Related Applications.

Other ink jet configurations can readily be derived from these forty-five examples by substituting alternative configurations along one or more of the 11 axes. Most of the IJ01 to IJ45 examples can be made into ink jet print heads printheads with characteristics superior to any currently available ink jet technology.

Where there are prior art examples known to the inventor, one or more of these examples are listed in the examples column of the tables below. The IJ01 to IJ45 series are also listed in the examples column. In some cases, print technology may be listed more than once in a table, where it shares characteristics with more than one entry.

Suitable applications for the ink jet technologies include: Home printers, Office network printers, Short run digital printers, Commercial print systems, Fabric printers, Pocket printers, Internet WWW printers, Video printers, Medical imaging, Wide format printers, Notebook PC printers, Fax machines, Industrial printing systems, Photocopiers, Photographic minilabs etc.

The information associated with the aforementioned 11 dimensional matrix are set out in the following tables.

ACTUATOR MECHANISM (APPLIED ONLY TO SELECTED INK DROPS)				
	Description	**Advantages**	**Disadvantages**	**Examples**
Thermal bubble	An electrothermal heater heats the ink to above boiling point, transferring significant heat to the aqueous ink. A bubble nucleates and quickly forms, expelling the ink. The efficiency of the process is low, with typically less than 0.05% of the electrical energy being transformed into kinetic energy of the drop.	♦ Large force generated ♦ Simple construction ♦ No moving parts ♦ Fast operation ♦ Small chip area required for actuator	♦ High power ♦ Ink carrier limited to water ♦ Low efficiency ♦ High temperatures required ♦ High mechanical stress ♦ Unusual materials required ♦ Large drive transistors ♦ Cavitation causes actuator failure ♦ Kogation reduces bubble formation ♦ Large print heads are difficult to fabricate	♦ Canon Bubblejet 1979 Endo et al GB patent 2,007,162 ♦ Xerox heater-in-pit 1990 Hawkins et al USP 4,899,181 ♦ Hewlett-Packard TIJ 1982 Vaught et al USP 4,490,728
Piezo-electric	A piezoelectric crystal such as lead lanthanum zirconate (PZT) is electrically activated, and either expands, shears, or bends to apply pressure to the ink, ejecting drops.	♦ Low power consumption ♦ Many ink types can be used ♦ Fast operation ♦ High efficiency	♦ Very large area required for actuator ♦ Difficult to integrate with electronics ♦ High voltage drive transistors required ♦ Full pagewidth print heads impractical due to actuator size ♦ Requires electrical poling in high field strengths during manufacture	♦ Kyser et al USP 3,946,398 ♦ Zoltan USP 3,683,212 ♦ 1973 Stemme USP 3,747,120 ♦ Epson Stylus ♦ Tektronix ♦ IJ04

ACTUATOR MECHANISM (APPLIED ONLY TO SELECTED INK DROPS)				
	Description	**Advantages**	**Disadvantages**	**Examples**
Electro-strictive	An electric field is used to activate electrostriction in relaxor materials such as lead lanthanum zirconate titanate (PLZT) or lead magnesium niobate (PMN).	♦ Low power consumption ♦ Many ink types can be used ♦ Low thermal expansion ♦ Electric field strength required (approx. 3.5 V/μm) can be generated without difficulty ♦ Does not require electrical poling	♦ Low maximum strain (approx. 0.01%) ♦ Large area required for actuator due to low strain ♦ Response speed is marginal (~ 10 μs) ♦ High voltage drive transistors required ♦ Full pagewidth print heads impractical due to actuator size	♦ .Seiko Epson, Usui et all JP 253401/96 ♦ IJ04
Ferro-electric	An electric field is used to induce a phase transition between the antiferroelectric (AFE) and ferroelectric (FE) phase. Perovskite materials such as tin modified lead lanthanum zirconate titanate (PLZSnT) exhibit large strains of up to 1% associated with the AFE to FE phase transition.	♦ Low power consumption ♦ Many ink types can be used ♦ Fast operation (< 1 μs) ♦ Relatively high longitudinal strain ♦ High efficiency ♦ Electric field strength of around 3 V/μm can be readily provided	♦ Difficult to integrate with electronics ♦ Unusual materials such as PLZSnT are required ♦ Actuators require a large area	♦ IJ04
Electro-static plates	Conductive plates are separated by a compressible or fluid dielectric (usually air). Upon application of a voltage, the plates attract each other and displace ink, causing drop ejection. The conductive plates may be in a comb or honeycomb structure, or stacked to increase the surface area and therefore the force.	♦ Low power consumption ♦ Many ink types can be used ♦ Fast operation	♦ Difficult to operate electrostatic devices in an aqueous environment ♦ The electrostatic actuator will normally need to be separated from the ink ♦ Very large area required to achieve high forces ♦ High voltage drive transistors may be required ♦ Full pagewidth print heads are not competitive due to actuator size	♦ IJ02, IJ04

ACTUATOR MECHANISM (APPLIED ONLY TO SELECTED INK DROPS)				
	Description	**Advantages**	**Disadvantages**	**Examples**
Electro-static pull on ink	A strong electric field is applied to the ink, whereupon electrostatic attraction accelerates the ink towards the print medium.	♦ Low current consumption ♦ Low temperature	♦ High voltage required ♦ May be damaged by sparks due to air breakdown ♦ Required field strength increases as the drop size decreases ♦ High voltage drive transistors required ♦ Electrostatic field attracts dust	♦ 1989 Saito et al, USP 4,799,068 ♦ 1989 Miura et al, USP 4,810,954 ♦ Tone-jet
Permanent magnet electro-magnetic	An electromagnet directly attracts a permanent magnet, displacing ink and causing drop ejection. Rare earth magnets with a field strength around 1 Tesla can be used. Examples are: Samarium Cobalt (SaCo) and magnetic materials in the neodymium iron boron family (NdFeB, NdDyFeBNb, NdDyFeB, etc)	♦ Low power consumption ♦ Many ink types can be used ♦ Fast operation ♦ High efficiency ♦ Easy extension from single nozzles to pagewidth print heads	♦ Complex fabrication ♦ Permanent magnetic material such as Neodymium Iron Boron (NdFeB) required. ♦ High local currents required ♦ Copper metalization should be used for long electromigration lifetime and low resistivity ♦ Pigmented inks are usually infeasible ♦ Operating temperature limited to the Curie temperature (around 540 K)	♦ IJ07, IJ10

ACTUATOR MECHANISM (APPLIED ONLY TO SELECTED INK DROPS)				
	Description	**Advantages**	**Disadvantages**	**Examples**
Soft magnetic core electro-magnetic	A solenoid induced a magnetic field in a soft magnetic core or yoke fabricated from a ferrous material such as electroplated iron alloys such as CoNiFe [1], CoFe, or NiFe alloys. Typically, the soft magnetic material is in two parts, which are normally held apart by a spring. When the solenoid is actuated, the two parts attract, displacing the ink.	♦ Low power consumption ♦ Many ink types can be used ♦ Fast operation ♦ High efficiency ♦ Easy extension from single nozzles to pagewidth print heads ♦	♦ Complex fabrication ♦ Materials not usually present in a CMOS fab such as NiFe, CoNiFe, or CoFe are required ♦ High local currents required ♦ Copper metalization should be used for long electromigration lifetime and low resistivity ♦ Electroplating is required ♦ High saturation flux density is required (2.0-2.1 T is achievable with CoNiFe [1])	♦ IJ01, IJ05, IJ08, IJ10, IJ12, IJ14, IJ15, IJ17
Lorenz force	The Lorenz force acting on a current carrying wire in a magnetic field is utilized. This allows the magnetic field to be supplied externally to the print head, for example with rare earth permanent magnets. Only the current carrying wire need be fabricated on the print-head, simplifying materials requirements.	♦ Low power consumption ♦ Many ink types can be used ♦ Fast operation ♦ High efficiency ♦ Easy extension from single nozzles to pagewidth print heads	♦ Force acts as a twisting motion ♦ Typically, only a quarter of the solenoid length provides force in a useful direction ♦ High local currents required ♦ Copper metalization should be used for long electromigration lifetime and low resistivity ♦ Pigmented inks are usually infeasible	♦ IJ06, IJ11, IJ13, IJ16

ACTUATOR MECHANISM (APPLIED ONLY TO SELECTED INK DROPS)				
	Description	Advantages	Disadvantages	Examples
Magneto-striction	The actuator uses the giant magnetostrictive effect of materials such as Terfenol-D (an alloy of terbium, dysprosium and iron developed at the Naval Ordnance Laboratory, hence Ter-Fe-NOL). For best efficiency, the actuator should be pre-stressed to approx. 8 MPa.	◆ Many ink types can be used ◆ Fast operation ◆ Easy extension from single nozzles to pagewidth print heads ◆ High force is available	◆ Force acts as a twisting motion ◆ Unusual materials such as Terfenol-D are required ◆ High local currents required ◆ Copper metalization should be used for long electromigration lifetime and low resistivity ◆ Pre-stressing may be required	◆ Fischenbeck, USP 4,032,929 ◆ IJ25
Surface tension reduction	Ink under positive pressure is held in a nozzle by surface tension. The surface tension of the ink is reduced below the bubble threshold, causing the ink to egress from the nozzle.	◆ Low power consumption ◆ Simple construction ◆ No unusual materials required in fabrication ◆ High efficiency ◆ Easy extension from single nozzles to pagewidth print heads	◆ Requires supplementary force to effect drop separation ◆ Requires special ink surfactants ◆ Speed may be limited by surfactant properties	◆ Silverbrook, EP 0771 658 A2 and related patent applications
Viscosity reduction	The ink viscosity is locally reduced to select which drops are to be ejected. A viscosity reduction can be achieved electrothermally with most inks, but special inks can be engineered for a 100:1 viscosity reduction.	◆ Simple construction ◆ No unusual materials required in fabrication ◆ Easy extension from single nozzles to pagewidth print heads	◆ Requires supplementary force to effect drop separation ◆ Requires special ink viscosity properties ◆ High speed is difficult to achieve ◆ Requires oscillating ink pressure ◆ A high temperature difference (typically 80 degrees) is required	◆ Silverbrook, EP 0771 658 A2 and related patent applications

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ACTUATOR MECHANISM (APPLIED ONLY TO SELECTED INK DROPS)				
	Description	**Advantages**	**Disadvantages**	**Examples**
Acoustic	An acoustic wave is generated and focussed upon the drop ejection region.	♦ Can operate without a nozzle plate	♦ Complex drive circuitry ♦ Complex fabrication ♦ Low efficiency ♦ Poor control of drop position ♦ Poor control of drop volume	♦ 1993 Hadimioglu et al, EUP 550,192 ♦ 1993 Elrod et al, EUP 572,220
Thermo-elastic bend actuator	An actuator which relies upon differential thermal expansion upon Joule heating is used.	♦ Low power consumption ♦ Many ink types can be used ♦ Simple planar fabrication ♦ Small chip area required for each actuator ♦ Fast operation ♦ High efficiency ♦ CMOS compatible voltages and currents ♦ Standard MEMS processes can be used ♦ Easy extension from single nozzles to pagewidth print heads	♦ Efficient aqueous operation requires a thermal insulator on the hot side ♦ Corrosion prevention can be difficult ♦ Pigmented inks may be infeasible, as pigment particles may jam the bend actuator	♦ IJ03, IJ09, IJ17, IJ18, IJ19, IJ20, IJ21, IJ22, IJ23, IJ24, IJ27, IJ28, IJ29, IJ30, IJ31, IJ32, IJ33, IJ34, IJ35, IJ36, IJ37, IJ38 ,IJ39, IJ40, IJ41

ACTUATOR MECHANISM (APPLIED ONLY TO SELECTED INK DROPS)				
	Description	**Advantages**	**Disadvantages**	**Examples**
High CTE thermo-elastic actuator	A material with a very high coefficient of thermal expansion (CTE) such as polytetrafluoroethylene (PTFE) is used. As high CTE materials are usually non-conductive, a heater fabricated from a conductive material is incorporated. A 50 μm long PTFE bend actuator with polysilicon heater and 15 mW power input can provide 180 μN force and 10 μm deflection. Actuator motions include: Bend Push Buckle Rotate	◆ High force can be generated ◆ Three methods of PTFE deposition are under development: chemical vapor deposition (CVD), spin coating, and evaporation ◆ PTFE is a candidate for low dielectric constant insulation in ULSI ◆ Very low power consumption ◆ Many ink types can be used ◆ Simple planar fabrication ◆ Small chip area required for each actuator ◆ Fast operation ◆ High efficiency ◆ CMOS compatible voltages and currents ◆ Easy extension from single nozzles to pagewidth print heads	◆ Requires special material (e.g. PTFE) ◆ Requires a PTFE deposition process, which is not yet standard in ULSI fabs ◆ PTFE deposition cannot be followed with high temperature (above 350 °C) processing ◆ Pigmented inks may be infeasible, as pigment particles may jam the bend actuator	◆ IJ09, IJ17, IJ18, IJ20, IJ21, IJ22, IJ23, IJ24, IJ27, IJ28, IJ29, IJ30, IJ31, IJ42, IJ43, IJ44

ACTUATOR MECHANISM (APPLIED ONLY TO SELECTED INK DROPS)				
	Description	**Advantages**	**Disadvantages**	**Examples**
Conduct-ive polymer thermo-elastic actuator	A polymer with a high coefficient of thermal expansion (such as PTFE) is doped with conducting substances to increase its conductivity to about 3 orders of magnitude below that of copper. The conducting polymer expands when resistively heated. Examples of conducting dopants include: Carbon nanotubes Metal fibers Conductive polymers such as doped polythiophene Carbon granules	◆ High force can be generated ◆ Very low power consumption ◆ Many ink types can be used ◆ Simple planar fabrication ◆ Small chip area required for each actuator ◆ Fast operation ◆ High efficiency ◆ CMOS compatible voltages and currents ◆ Easy extension from single nozzles to pagewidth print heads	◆ Requires special materials development (High CTE conductive polymer) ◆ Requires a PTFE deposition process, which is not yet standard in ULSI fabs ◆ PTFE deposition cannot be followed with high temperature (above 350 °C) processing ◆ Evaporation and CVD deposition techniques cannot be used ◆ Pigmented inks may be infeasible, as pigment particles may jam the bend actuator	◆ IJ24
Shape memory alloy	A shape memory alloy such as TiNi (also known as Nitinol - Nickel Titanium alloy developed at the Naval Ordnance Laboratory) is thermally switched between its weak martensitic state and its high stiffness austenic state. The shape of the actuator in its martensitic state is deformed relative to the austenic shape. The shape change causes ejection of a drop.	◆ High force is available (stresses of hundreds of MPa) ◆ Large strain is available (more than 3%) ◆ High corrosion resistance ◆ Simple construction ◆ Easy extension from single nozzles to pagewidth print heads ◆ Low voltage operation	◆ Fatigue limits maximum number of cycles ◆ Low strain (1%) is required to extend fatigue resistance ◆ Cycle rate limited by heat removal ◆ Requires unusual materials (TiNi) ◆ The latent heat of transformation must be provided ◆ High current operation ◆ Requires pre-stressing to distort the martensitic state	◆ IJ26

ACTUATOR MECHANISM (APPLIED ONLY TO SELECTED INK DROPS)				
	Description	**Advantages**	**Disadvantages**	**Examples**
Linear Magnetic Actuator	Linear magnetic actuators include the Linear Induction Actuator (LIA), Linear Permanent Magnet Synchronous Actuator (LPMSA), Linear Reluctance Synchronous Actuator (LRSA), Linear Switched Reluctance Actuator (LSRA), and the Linear Stepper Actuator (LSA).	◆ Linear Magnetic actuators can be constructed with high thrust, long travel, and high efficiency using planar semiconductor fabrication techniques ◆ Long actuator travel is available ◆ Medium force is available ◆ Low voltage operation	◆ Requires unusual semiconductor materials such as soft magnetic alloys (e.g. CoNiFe) ◆ Some varieties also require permanent magnetic materials such as Neodymium iron boron (NdFeB) ◆ Requires complex multi-phase drive circuitry ◆ High current operation	◆ IJ12

BASIC OPERATION MODE				
	Description	**Advantages**	**Disadvantages**	**Examples**
Actuator directly pushes ink	This is the simplest mode of operation: the actuator directly supplies sufficient kinetic energy to expel the drop. The drop must have a sufficient velocity to overcome the surface tension.	◆ Simple operation ◆ No external fields required ◆ Satellite drops can be avoided if drop velocity is less than 4 m/s ◆ Can be efficient, depending upon the actuator used	◆ Drop repetition rate is usually limited to around 10 kHz. However, this is not fundamental to the method, but is related to the refill method normally used ◆ All of the drop kinetic energy must be provided by the actuator ◆ Satellite drops usually form if drop velocity is greater than 4.5 m/s	◆ Thermal ink jet ◆ Piezoelectric ink jet ◆ IJ01, IJ02, IJ03, IJ04, IJ05, IJ06, IJ07, IJ09, IJ11, IJ12, IJ14, IJ16, IJ20, IJ22, IJ23, IJ24, IJ25, IJ26, IJ27, IJ28, IJ29, IJ30, IJ31, IJ32, IJ33, IJ34, IJ35, IJ36, IJ37, IJ38, IJ39, IJ40, IJ41, IJ42, IJ43, IJ44
Proximity	The drops to be printed are selected by some manner (e.g. thermally induced surface tension reduction of pressurized ink). Selected drops are separated from the ink in the nozzle by contact with the print medium or a transfer roller.	◆ Very simple print head fabrication can be used ◆ The drop selection means does not need to provide the energy required to separate the drop from the nozzle	◆ Requires close proximity between the print head and the print media or transfer roller ◆ May require two print heads printing alternate rows of the image ◆ Monolithic color print heads are difficult	◆ Silverbrook, EP 0771 658 A2 and related patent applications

BASIC OPERATION MODE				
	Description	**Advantages**	**Disadvantages**	**Examples**
Electro-static pull on ink	The drops to be printed are selected by some manner (e.g. thermally induced surface tension reduction of pressurized ink). Selected drops are separated from the ink in the nozzle by a strong electric field.	♦ Very simple print head fabrication can be used ♦ The drop selection means does not need to provide the energy required to separate the drop from the nozzle	♦ Requires very high electrostatic field ♦ Electrostatic field for small nozzle sizes is above air breakdown ♦ Electrostatic field may attract dust	♦ Silverbrook, EP 0771 658 A2 and related patent applications ♦ Tone-Jet
Magnetic pull on ink	The drops to be printed are selected by some manner (e.g. thermally induced surface tension reduction of pressurized ink). Selected drops are separated from the ink in the nozzle by a strong magnetic field acting on the magnetic ink.	♦ Very simple print head fabrication can be used ♦ The drop selection means does not need to provide the energy required to separate the drop from the nozzle	♦ Requires magnetic ink ♦ Ink colors other than black are difficult ♦ Requires very high magnetic fields	♦ Silverbrook, EP 0771 658 A2 and related patent applications
Shutter	The actuator moves a shutter to block ink flow to the nozzle. The ink pressure is pulsed at a multiple of the drop ejection frequency.	♦ High speed (>50 kHz) operation can be achieved due to reduced refill time ♦ Drop timing can be very accurate ♦ The actuator energy can be very low	♦ Moving parts are required ♦ Requires ink pressure modulator ♦ Friction and wear must be considered ♦ Stiction is possible	♦ IJ13, IJ17, IJ21
Shuttered grill	The actuator moves a shutter to block ink flow through a grill to the nozzle. The shutter movement need only be equal to the width of the grill holes.	♦ Actuators with small travel can be used ♦ Actuators with small force can be used ♦ High speed (>50 kHz) operation can be achieved	♦ Moving parts are required ♦ Requires ink pressure modulator ♦ Friction and wear must be considered ♦ Stiction is possible	♦ IJ08, IJ15, IJ18, IJ19
Pulsed magnetic pull on ink pusher	A pulsed magnetic field attracts an 'ink pusher' at the drop ejection frequency. An actuator controls a catch, which prevents the ink pusher from moving when a drop is not to be ejected.	♦ Extremely low energy operation is possible ♦ No heat dissipation problems	♦ Requires an external pulsed magnetic field ♦ Requires special materials for both the actuator and the ink pusher ♦ Complex construction	♦ IJ10

AUXILIARY MECHANISM (APPLIED TO ALL NOZZLES)				
	Description	**Advantages**	**Disadvantages**	**Examples**
None	The actuator directly fires the ink drop, and there is no external field or other mechanism required.	♦ Simplicity of construction ♦ Simplicity of operation ♦ Small physical size	♦ Drop ejection energy must be supplied by individual nozzle actuator	♦ Most ink jets, including piezoelectric and thermal bubble. ♦ IJ01, IJ02, IJ03, IJ04, IJ05, IJ07, IJ09, IJ11, IJ12, IJ14, IJ20, IJ22, IJ23, IJ24, IJ25, IJ26, IJ27, IJ28, IJ29, IJ30, IJ31, IJ32, IJ33, IJ34, IJ35, IJ36, IJ37, IJ38, IJ39, IJ40, IJ41, IJ42, IJ43, IJ44
Oscillating ink pressure (including acoustic stimul-ation)	The ink pressure oscillates, providing much of the drop ejection energy. The actuator selects which drops are to be fired by selectively blocking or enabling nozzles. The ink pressure oscillation may be achieved by vibrating the print head, or preferably by an actuator in the ink supply.	♦ Oscillating ink pressure can provide a refill pulse, allowing higher operating speed ♦ The actuators may operate with much lower energy ♦ Acoustic lenses can be used to focus the sound on the nozzles	♦ Requires external ink pressure oscillator ♦ Ink pressure phase and amplitude must be carefully controlled ♦ Acoustic reflections in the ink chamber must be designed for	♦ Silverbrook, EP 0771 658 A2 and related patent applications ♦ IJ08, IJ13, IJ15, IJ17, IJ18, IJ19, IJ21
Media proximity	The print head is placed in close proximity to the print medium. Selected drops protrude from the print head further than unselected drops, and contact the print medium. The drop soaks into the medium fast enough to cause drop separation.	♦ Low power ♦ High accuracy ♦ Simple print head construction	♦ Precision assembly required ♦ Paper fibers may cause problems ♦ Cannot print on rough substrates	♦ Silverbrook, EP 0771 658 A2 and related patent applications
Transfer roller	Drops are printed to a transfer roller instead of straight to the print medium. A transfer roller can also be used for proximity drop separation.	♦ High accuracy ♦ Wide range of print substrates can be used ♦ Ink can be dried on the transfer roller	♦ Bulky ♦ Expensive ♦ Complex construction	♦ Silverbrook, EP 0771 658 A2 and related patent applications ♦ Tektronix hot melt piezoelectric ink jet ♦ Any of the IJ series

AUXILIARY MECHANISM (APPLIED TO ALL NOZZLES)				
	Description	**Advantages**	**Disadvantages**	**Examples**
Electro-static	An electric field is used to accelerate selected drops towards the print medium.	◆ Low power ◆ Simple print head construction	◆ Field strength required for separation of small drops is near or above air breakdown	◆ Silverbrook, EP 0771 658 A2 and related patent applications ◆ Tone-Jet
Direct magnetic field	A magnetic field is used to accelerate selected drops of magnetic ink towards the print medium.	◆ Low power ◆ Simple print head construction	◆ Requires magnetic ink ◆ Requires strong magnetic field	◆ Silverbrook, EP 0771 658 A2 and related patent applications
Cross magnetic field	The print head is placed in a constant magnetic field. The Lorenz force in a current carrying wire is used to move the actuator.	◆ Does not require magnetic materials to be integrated in the print head manufacturing process	◆ Requires external magnet ◆ Current densities may be high, resulting in electromigration problems	◆ IJ06, IJ16
Pulsed magnetic field	A pulsed magnetic field is used to cyclically attract a paddle, which pushes on the ink. A small actuator moves a catch, which selectively prevents the paddle from moving.	◆ Very low power operation is possible ◆ Small print head size	◆ Complex print head construction ◆ Magnetic materials required in print head	◆ IJ10

ACTUATOR AMPLIFICATION OR MODIFICATION METHOD				
	Description	**Advantages**	**Disadvantages**	**Examples**
None	No actuator mechanical amplification is used. The actuator directly drives the drop ejection process.	♦ Operational simplicity	♦ Many actuator mechanisms have insufficient travel, or insufficient force, to efficiently drive the drop ejection process	♦ Thermal Bubble Ink jet ♦ IJ01, IJ02, IJ06, IJ07, IJ16, IJ25, IJ26
Differential expansion bend actuator	An actuator material expands more on one side than on the other. The expansion may be thermal, piezoelectric, magnetostrictive, or other mechanism. The bend actuator converts a high force low travel actuator mechanism to high travel, lower force mechanism.	♦ Provides greater travel in a reduced print head area	♦ High stresses are involved ♦ Care must be taken that the materials do not delaminate ♦ Residual bend resulting from high temperature or high stress during formation	♦ Piezoelectric ♦ IJ03, IJ09, IJ17, IJ18, IJ19, IJ20, IJ21, IJ22, IJ23, IJ24, IJ27, IJ29, IJ30, IJ31, IJ32, IJ33, IJ34, IJ35, IJ36, IJ37, IJ38, IJ39, IJ42, IJ43, IJ44
Transient bend actuator	A trilayer bend actuator where the two outside layers are identical. This cancels bend due to ambient temperature and residual stress. The actuator only responds to transient heating of one side or the other.	♦ Very good temperature stability ♦ High speed, as a new drop can be fired before heat dissipates ♦ Cancels residual stress of formation	♦ High stresses are involved ♦ Care must be taken that the materials do not delaminate	♦ IJ40, IJ41
Reverse spring	The actuator loads a spring. When the actuator is turned off, the spring releases. This can reverse the force/distance curve of the actuator to make it compatible with the force/time requirements of the drop ejection.	♦ Better coupling to the ink	♦ Fabrication complexity ♦ High stress in the spring	♦ IJ05, IJ11
Actuator stack	A series of thin actuators are stacked. This can be appropriate where actuators require high electric field strength, such as electrostatic and piezoelectric actuators.	♦ Increased travel ♦ Reduced drive voltage	♦ Increased fabrication complexity ♦ Increased possibility of short circuits due to pinholes	♦ Some piezoelectric ink jets ♦ IJ04

ACTUATOR AMPLIFICATION OR MODIFICATION METHOD				
	Description	**Advantages**	**Disadvantages**	**Examples**
Multiple actuators	Multiple smaller actuators are used simultaneously to move the ink. Each actuator need provide only a portion of the force required.	◆ Increases the force available from an actuator ◆ Multiple actuators can be positioned to control ink flow accurately	◆ Actuator forces may not add linearly, reducing efficiency	◆ IJ12, IJ13, IJ18, IJ20, IJ22, IJ28, IJ42, IJ43
Linear Spring	A linear spring is used to transform a motion with small travel and high force into a longer travel, lower force motion.	◆ Matches low travel actuator with higher travel requirements ◆ Non-contact method of motion transformation	◆ Requires print head area for the spring	◆ IJ15
Coiled actuator	A bend actuator is coiled to provide greater travel in a reduced chip area.	◆ Increases travel ◆ Reduces chip area ◆ Planar implementations are relatively easy to fabricate.	◆ Generally restricted to planar implementations due to extreme fabrication difficulty in other orientations.	◆ IJ17, IJ21, IJ34, IJ35
Flexure bend actuator	A bend actuator has a small region near the fixture point, which flexes much more readily than the remainder of the actuator. The actuator flexing is effectively converted from an even coiling to an angular bend, resulting in greater travel of the actuator tip.	◆ Simple means of increasing travel of a bend actuator	◆ Care must be taken not to exceed the elastic limit in the flexure area ◆ Stress distribution is very uneven ◆ Difficult to accurately model with finite element analysis	◆ IJ10, IJ19, IJ33
Catch	The actuator controls a small catch. The catch either enables or disables movement of an ink pusher that is controlled in a bulk manner.	◆ Very low actuator energy ◆ Very small actuator size	◆ Complex construction ◆ Requires external force ◆ Unsuitable for pigmented inks	◆ IJ10
Gears	Gears can be used to increase travel at the expense of duration. Circular gears, rack and pinion, ratchets, and other gearing methods can be used.	◆ Low force, low travel actuators can be used ◆ Can be fabricated using standard surface MEMS processes	◆ Moving parts are required ◆ Several actuator cycles are required ◆ More complex drive electronics ◆ Complex construction ◆ Friction, friction, and wear are possible	◆ IJ13

ACTUATOR AMPLIFICATION OR MODIFICATION METHOD				
	Description	**Advantages**	**Disadvantages**	**Examples**
Buckle plate	A buckle plate can be used to change a slow actuator into a fast motion. It can also convert a high force, low travel actuator into a high travel, medium force motion.	◆ Very fast movement achievable	◆ Must stay within elastic limits of the materials for long device life ◆ High stresses involved ◆ Generally high power requirement	◆ S. Hirata et al, "An Ink-jet Head Using Diaphragm Microactuator", Proc. IEEE MEMS, Feb. 1996, pp 418-423. ◆ IJ18, IJ27
Tapered magnetic pole	A tapered magnetic pole can increase travel at the expense of force.	◆ Linearizes the magnetic force/distance curve	◆ Complex construction	◆ IJ14
Lever	A lever and fulcrum is used to transform a motion with small travel and high force into a motion with longer travel and lower force. The lever can also reverse the direction of travel.	◆ Matches low travel actuator with higher travel requirements ◆ Fulcrum area has no linear movement, and can be used for a fluid seal	◆ High stress around the fulcrum	◆ IJ32, IJ36, IJ37
Rotary impeller	The actuator is connected to a rotary impeller. A small angular deflection of the actuator results in a rotation of the impeller vanes, which push the ink against stationary vanes and out of the nozzle.	◆ High mechanical advantage ◆ The ratio of force to travel of the actuator can be matched to the nozzle requirements by varying the number of impeller vanes	◆ Complex construction ◆ Unsuitable for pigmented inks	◆ IJ28
Acoustic lens	A refractive or diffractive (e.g. zone plate) acoustic lens is used to concentrate sound waves.	◆ No moving parts	◆ Large area required ◆ Only relevant for acoustic ink jets	◆ 1993 Hadimioglu et al, EUP 550,192 ◆ 1993 Elrod et al, EUP 572,220
Sharp conductive point	A sharp point is used to concentrate an electrostatic field.	◆ Simple construction	◆ Difficult to fabricate using standard VLSI processes for a surface ejecting ink-jet ◆ Only relevant for electrostatic ink jets	◆ Tone-jet

ACTUATOR MOTION				
	Description	**Advantages**	**Disadvantages**	**Examples**
Volume expansion	The volume of the actuator changes, pushing the ink in all directions.	◆ Simple construction in the case of thermal ink jet	◆ High energy is typically required to achieve volume expansion. This leads to thermal stress, cavitation, and kogation in thermal ink jet implementations	◆ Hewlett-Packard Thermal Ink jet ◆ Canon Bubblejet
Linear, normal to chip surface	The actuator moves in a direction normal to the print head surface. The nozzle is typically in the line of movement.	◆ Efficient coupling to ink drops ejected normal to the surface	◆ High fabrication complexity may be required to achieve perpendicular motion	◆ IJ01, IJ02, IJ04, IJ07, IJ11, IJ14
Parallel to chip surface	The actuator moves parallel to the print head surface. Drop ejection may still be normal to the surface.	◆ Suitable for planar fabrication	◆ Fabrication complexity ◆ Friction ◆ Stiction	◆ IJ12, IJ13, IJ15, IJ33, , IJ34, IJ35, IJ36
Membrane push	An actuator with a high force but small area is used to push a stiff membrane that is in contact with the ink.	◆ The effective area of the actuator becomes the membrane area	◆ Fabrication complexity ◆ Actuator size ◆ Difficulty of integration in a VLSI process	◆ 1982 Howkins USP 4,459,601
Rotary	The actuator causes the rotation of some element, such a grill or impeller	◆ Rotary levers may be used to increase travel ◆ Small chip area requirements	◆ Device complexity ◆ May have friction at a pivot point	◆ IJ05, IJ08, IJ13, IJ28
Bend	The actuator bends when energized. This may be due to differential thermal expansion, piezoelectric expansion, magnetostriction, or other form of relative dimensional change.	◆ A very small change in dimensions can be converted to a large motion.	◆ Requires the actuator to be made from at least two distinct layers, or to have a thermal difference across the actuator	◆ 1970 Kyser et al USP 3,946,398 ◆ 1973 Stemme USP 3,747,120 ◆ IJ03, IJ09, IJ10, IJ19, IJ23, IJ24, IJ25, IJ29, IJ30, IJ31, IJ33, IJ34, IJ35
Swivel	The actuator swivels around a central pivot. This motion is suitable where there are opposite forces applied to opposite sides of the paddle, e.g. Lorenz force.	◆ Allows operation where the net linear force on the paddle is zero ◆ Small chip area requirements	◆ Inefficient coupling to the ink motion	◆ IJ06

ACTUATOR MOTION				
	Description	**Advantages**	**Disadvantages**	**Examples**
Straighten	The actuator is normally bent, and straightens when energized.	◆ Can be used with shape memory alloys where the austenic phase is planar	◆ Requires careful balance of stresses to ensure that the quiescent bend is accurate	◆ IJ26, IJ32
Double bend	The actuator bends in one direction when one element is energized, and bends the other way when another element is energized.	◆ One actuator can be used to power two nozzles. ◆ Reduced chip size. ◆ Not sensitive to ambient temperature	◆ Difficult to make the drops ejected by both bend directions identical. ◆ A small efficiency loss compared to equivalent single bend actuators.	◆ IJ36, IJ37, IJ38
Shear	Energizing the actuator causes a shear motion in the actuator material.	◆ Can increase the effective travel of piezoelectric actuators	◆ Not readily applicable to other actuator mechanisms	◆ 1985 Fishbeck USP 4,584,590
Radial con-striction	The actuator squeezes an ink reservoir, forcing ink from a constricted nozzle.	◆ Relatively easy to fabricate single nozzles from glass tubing as macroscopic structures	◆ High force required ◆ Inefficient ◆ Difficult to integrate with VLSI processes	◆ 1970 Zoltan USP 3,683,212
Coil / uncoil	A coiled actuator uncoils or coils more tightly. The motion of the free end of the actuator ejects the ink.	◆ Easy to fabricate as a planar VLSI process ◆ Small area required, therefore low cost	◆ Difficult to fabricate for non-planar devices ◆ Poor out-of-plane stiffness	◆ IJ17, IJ21, IJ34, IJ35
Bow	The actuator bows (or buckles) in the middle when energized.	◆ Can increase the speed of travel ◆ Mechanically rigid	◆ Maximum travel is constrained ◆ High force required	◆ IJ16, IJ18, IJ27
Push-Pull	Two actuators control a shutter. One actuator pulls the shutter, and the other pushes it.	◆ The structure is pinned at both ends, so has a high out-of-plane rigidity	◆ Not readily suitable for ink jets which directly push the ink	◆ IJ18
Curl inwards	A set of actuators curl inwards to reduce the volume of ink that they enclose.	◆ Good fluid flow to the region behind the actuator increases efficiency	◆ Design complexity	◆ IJ20, IJ42
Curl outwards	A set of actuators curl outwards, pressurizing ink in a chamber surrounding the actuators, and expelling ink from a nozzle in the chamber.	◆ Relatively simple construction	◆ Relatively large chip area	◆ IJ43

ACTUATOR MOTION				
	Description	**Advantages**	**Disadvantages**	**Examples**
Iris	Multiple vanes enclose a volume of ink. These simultaneously rotate, reducing the volume between the vanes.	♦ High efficiency ♦ Small chip area	♦ High fabrication complexity ♦ Not suitable for pigmented inks	♦ IJ22
Acoustic vibration	The actuator vibrates at a high frequency.	♦ The actuator can be physically distant from the ink	♦ Large area required for efficient operation at useful frequencies ♦ Acoustic coupling and crosstalk ♦ Complex drive circuitry ♦ Poor control of drop volume and position	♦ 1993 Hadimioglu et al, EUP 550,192 ♦ 1993 Elrod et al, EUP 572,220
None	In various ink jet designs the actuator does not move.	♦ No moving parts	♦ Various other tradeoffs are required to eliminate moving parts	♦ Silverbrook, EP 0771 658 A2 and related patent applications ♦ Tone-jet

NOZZLE REFILL METHOD				
	Description	**Advantages**	**Disadvantages**	**Examples**
Surface tension	This is the normal way that ink jets are refilled. After the actuator is energized, it typically returns rapidly to its normal position. This rapid return sucks in air through the nozzle opening. The ink surface tension at the nozzle then exerts a small force restoring the meniscus to a minimum area. This force refills the nozzle.	♦ Fabrication simplicity ♦ Operational simplicity	♦ Low speed ♦ Surface tension force relatively small compared to actuator force ♦ Long refill time usually dominates the total repetition rate	♦ Thermal ink jet ♦ Piezoelectric ink jet ♦ IJ01-IJ07, IJ10-IJ14, IJ16, IJ20, IJ22-IJ45
Shuttered oscillating ink pressure	Ink to the nozzle chamber is provided at a pressure that oscillates at twice the drop ejection frequency. When a drop is to be ejected, the shutter is opened for 3 half cycles: drop ejection, actuator return, and refill. The shutter is then closed to prevent the nozzle chamber emptying during the next negative pressure cycle.	♦ High speed ♦ Low actuator energy, as the actuator need only open or close the shutter, instead of ejecting the ink drop	♦ Requires common ink pressure oscillator ♦ May not be suitable for pigmented inks	♦ IJ08, IJ13, IJ15, IJ17, IJ18, IJ19, IJ21
Refill actuator	After the main actuator has ejected a drop a second (refill) actuator is energized. The refill actuator pushes ink into the nozzle chamber. The refill actuator returns slowly, to prevent its return from emptying the chamber again.	♦ High speed, as the nozzle is actively refilled	♦ Requires two independent actuators per nozzle	♦ IJ09
Positive ink pressure	The ink is held a slight positive pressure. After the ink drop is ejected, the nozzle chamber fills quickly as surface tension and ink pressure both operate to refill the nozzle.	♦ High refill rate, therefore a high drop repetition rate is possible	♦ Surface spill must be prevented ♦ Highly hydrophobic print head surfaces are required	♦ Silverbrook, EP 0771 658 A2 and related patent applications ♦ Alternative for:, IJ01-IJ07, IJ10-IJ14, IJ16, IJ20, IJ22-IJ45

METHOD OF RESTRICTING BACK-FLOW THROUGH INLET				
	Description	**Advantages**	**Disadvantages**	**Examples**
Long inlet channel	The ink inlet channel to the nozzle chamber is made long and relatively narrow, relying on viscous drag to reduce inlet back-flow.	◆ Design simplicity ◆ Operational simplicity ◆ Reduces crosstalk	◆ Restricts refill rate ◆ May result in a relatively large chip area ◆ Only partially effective	◆ Thermal ink jet ◆ Piezoelectric ink jet ◆ IJ42, IJ43
Positive ink pressure	The ink is under a positive pressure, so that in the quiescent state some of the ink drop already protrudes from the nozzle. This reduces the pressure in the nozzle chamber which is required to eject a certain volume of ink. The reduction in chamber pressure results in a reduction in ink pushed out through the inlet.	◆ Drop selection and separation forces can be reduced ◆ Fast refill time	◆ Requires a method (such as a nozzle rim or effective hydrophobizing, or both) to prevent flooding of the ejection surface of the print head.	◆ Silverbrook, EP 0771 658 A2 and related patent applications ◆ Possible operation of the following: IJ01-IJ07, IJ09- IJ12, IJ14, IJ16, IJ20, IJ22, , IJ23-IJ34, IJ36- IJ41, IJ44
Baffle	One or more baffles are placed in the inlet ink flow. When the actuator is energized, the rapid ink movement creates eddies which restrict the flow through the inlet. The slower refill process is unrestricted, and does not result in eddies.	◆ The refill rate is not as restricted as the long inlet method. ◆ Reduces crosstalk	◆ Design complexity ◆ May increase fabrication complexity (e.g. Tektronix hot melt Piezoelectric print heads).	◆ HP Thermal Ink Jet ◆ Tektronix piezoelectric ink jet
Flexible flap restricts inlet	In this method recently disclosed by Canon, the expanding actuator (bubble) pushes on a flexible flap that restricts the inlet.	◆ Significantly reduces back-flow for edge-shooter thermal ink jet devices	◆ Not applicable to most ink jet configurations ◆ Increased fabrication complexity ◆ Inelastic deformation of polymer flap results in creep over extended use	◆ Canon

METHOD OF RESTRICTING BACK-FLOW THROUGH INLET				
	Description	**Advantages**	**Disadvantages**	**Examples**
Inlet filter	A filter is located between the ink inlet and the nozzle chamber. The filter has a multitude of small holes or slots, restricting ink flow. The filter also removes particles which may block the nozzle.	◆ Additional advantage of ink filtration ◆ Ink filter may be fabricated with no additional process steps	◆ Restricts refill rate ◆ May result in complex construction	◆ IJ04, IJ12, IJ24, IJ27, IJ29, IJ30
Small inlet compared to nozzle	The ink inlet channel to the nozzle chamber has a substantially smaller cross section than that of the nozzle , resulting in easier ink egress out of the nozzle than out of the inlet.	◆ Design simplicity	◆ Restricts refill rate ◆ May result in a relatively large chip area ◆ Only partially effective	◆ IJ02, IJ37, IJ44
Inlet shutter	A secondary actuator controls the position of a shutter, closing off the ink inlet when the main actuator is energized.	◆ Increases speed of the ink-jet print head operation	◆ Requires separate refill actuator and drive circuit	◆ IJ09
The inlet is located behind the ink-pushing surface	The method avoids the problem of inlet back-flow by arranging the ink-pushing surface of the actuator between the inlet and the nozzle.	◆ Back-flow problem is eliminated	◆ Requires careful design to minimize the negative pressure behind the paddle	◆ IJ01, IJ03, 1J05, IJ06, IJ07, IJ10, IJ11, IJ14, IJ16, IJ22, IJ23, IJ25, IJ28, IJ31, IJ32, IJ33, IJ34, IJ35, IJ36, IJ39, IJ40, IJ41
Part of the actuator moves to shut off the inlet	The actuator and a wall of the ink chamber are arranged so that the motion of the actuator closes off the inlet.	◆ Significant reductions in back-flow can be achieved ◆ Compact designs possible	◆ Small increase in fabrication complexity	◆ IJ07, IJ20, IJ26, IJ38
Nozzle actuator does not result in ink back-flow	In some configurations of ink jet, there is no expansion or movement of an actuator which may cause ink back-flow through the inlet.	◆ Ink back-flow problem is eliminated	◆ None related to ink back-flow on actuation	◆ Silverbrook, EP 0771 658 A2 and related patent applications ◆ Valve-jet ◆ Tone-jet

NOZZLE CLEARING METHOD				
	Description	**Advantages**	**Disadvantages**	**Examples**
Normal nozzle firing	All of the nozzles are fired periodically, before the ink has a chance to dry. When not in use the nozzles are sealed (capped) against air. The nozzle firing is usually performed during a special clearing cycle, after first moving the print head to a cleaning station.	♦ No added complexity on the print head	♦ May not be sufficient to displace dried ink	♦ Most ink jet systems ♦ IJ01, IJ02, IJ03, IJ04, IJ05, IJ06, IJ07, IJ09, IJ10, IJ11, IJ12, IJ14, IJ16, IJ20, IJ22, IJ23, IJ24, IJ25, IJ26, IJ27, IJ28, IJ29, IJ30, IJ31, IJ32, IJ33, IJ34, IJ36, IJ37, IJ38, IJ39, IJ40,, IJ41, IJ42, IJ43, IJ44,, IJ45
Extra power to ink heater	In systems which heat the ink, but do not boil it under normal situations, nozzle clearing can be achieved by over-powering the heater and boiling ink at the nozzle.	♦ Can be highly effective if the heater is adjacent to the nozzle	♦ Requires higher drive voltage for clearing ♦ May require larger drive transistors	♦ Silverbrook, EP 0771 658 A2 and related patent applications
Rapid success-ion of actuator pulses	The actuator is fired in rapid succession. In some configurations, this may cause heat build-up at the nozzle which boils the ink, clearing the nozzle. In other situations, it may cause sufficient vibrations to dislodge clogged nozzles.	♦ Does not require extra drive circuits on the print head ♦ Can be readily controlled and initiated by digital logic	♦ Effectiveness depends substantially upon the configuration of the ink jet nozzle	♦ May be used with: IJ01, IJ02, IJ03, IJ04, IJ05, IJ06, IJ07, IJ09, IJ10, IJ11, IJ14, IJ16, IJ20, IJ22, IJ23, IJ24, IJ25, IJ27, IJ28, IJ29, IJ30, IJ31, IJ32, IJ33, IJ34, IJ36, IJ37, IJ38, IJ39, IJ40, IJ41, IJ42, IJ43, IJ44, IJ45
Extra power to ink pushing actuator	Where an actuator is not normally driven to the limit of its motion, nozzle clearing may be assisted by providing an enhanced drive signal to the actuator.	♦ A simple solution where applicable	♦ Not suitable where there is a hard limit to actuator movement	♦ May be used with: IJ03, IJ09, IJ16, IJ20, IJ23, IJ24, IJ25, IJ27, IJ29, IJ30, IJ31, IJ32, IJ39, IJ40, IJ41, IJ42, IJ43, IJ44, IJ45

NOZZLE CLEARING METHOD				
	Description	**Advantages**	**Disadvantages**	**Examples**
Acoustic resonance	An ultrasonic wave is applied to the ink chamber. This wave is of an appropriate amplitude and frequency to cause sufficient force at the nozzle to clear blockages. This is easiest to achieve if the ultrasonic wave is at a resonant frequency of the ink cavity.	◆ A high nozzle clearing capability can be achieved ◆ May be implemented at very low cost in systems which already include acoustic actuators	◆ High implementation cost if system does not already include an acoustic actuator	◆ IJ08, IJ13, IJ15, IJ17, IJ18, IJ19, IJ21
Nozzle clearing plate	A microfabricated plate is pushed against the nozzles. The plate has a post for every nozzle. A post moves through each nozzle, displacing dried ink.	◆ Can clear severely clogged nozzles	◆ Accurate mechanical alignment is required ◆ Moving parts are required ◆ There is risk of damage to the nozzles ◆ Accurate fabrication is required	◆ Silverbrook, EP 0771 658 A2 and related patent applications
Ink pressure pulse	The pressure of the ink is temporarily increased so that ink streams from all of the nozzles. This may be used in conjunction with actuator energizing.	◆ May be effective where other methods cannot be used	◆ Requires pressure pump or other pressure actuator ◆ Expensive ◆ Wasteful of ink	◆ May be used with all IJ series ink jets
Print head wiper	A flexible 'blade' is wiped across the print head surface. The blade is usually fabricated from a flexible polymer, e.g. rubber or synthetic elastomer.	◆ Effective for planar print head surfaces ◆ Low cost	◆ Difficult to use if print head surface is non-planar or very fragile ◆ Requires mechanical parts ◆ Blade can wear out in high volume print systems	◆ Many ink jet systems

NOZZLE CLEARING METHOD				
	Description	**Advantages**	**Disadvantages**	**Examples**
Separate ink boiling heater	A separate heater is provided at the nozzle although the normal drop e–ection mechanism does not require it. The heaters do not require individual drive circuits, as many nozzles can be cleared simultaneously, and no imaging is required.	♦ Can be effective where other nozzle clearing methods cannot be used ♦ Can be implemented at no additional cost in some ink jet configurations	♦ Fabrication complexity	♦ Can be used with many IJ series ink jets

NOZZLE PLATE CONSTRUCTION				
	Description	**Advantages**	**Disadvantages**	**Examples**
Electro-formed nickel	A nozzle plate is separately fabricated from electroformed nickel, and bonded to the print head chip.	◆ Fabrication simplicity	◆ High temperatures and pressures are required to bond nozzle plate ◆ Minimum thickness constraints ◆ Differential thermal expansion	◆ Hewlett Packard Thermal Ink jet
Laser ablated or drilled polymer	Individual nozzle holes are ablated by an intense UV laser in a nozzle plate, which is typically a polymer such as polyimide or polysulphone	◆ No masks required ◆ Can be quite fast ◆ Some control over nozzle profile is possible ◆ Equipment required is relatively low cost	◆ Each hole must be individually formed ◆ Special equipment required ◆ Slow where there are many thousands of nozzles per print head ◆ May produce thin burrs at exit holes	◆ Canon Bubblejet ◆ 1988 Sercel et al., SPIE, Vol. 998 Excimer Beam Applications, pp. 76-83 ◆ 1993 Watanabe et al., USP 5,208,604
Silicon micro-machined	A separate nozzle plate is micromachined from single crystal silicon, and bonded to the print head wafer.	◆ High accuracy is attainable	◆ Two part construction ◆ High cost ◆ Requires precision alignment ◆ Nozzles may be clogged by adhesive	◆ K. Bean, IEEE Transactions on Electron Devices, Vol. ED-25, No. 10, 1978, pp 1185-1195 ◆ Xerox 1990 Hawkins et al., USP 4,899,181
Glass capillaries	Fine glass capillaries are drawn from glass tubing. This method has been used for making individual nozzles, but is difficult to use for bulk manufacturing of print heads with thousands of nozzles.	◆ No expensive equipment required ◆ Simple to make single nozzles	◆ Very small nozzle sizes are difficult to form ◆ Not suited for mass production	◆ 1970 Zoltan USP 3,683,212
Monolithic, surface micro-machined using VLSI litho-graphic processes	The nozzle plate is deposited as a layer using standard VLSI deposition techniques. Nozzles are etched in the nozzle plate using VLSI lithography and etching.	◆ High accuracy (<1 μm) ◆ Monolithic ◆ Low cost ◆ Existing processes can be used	◆ Requires sacrificial layer under the nozzle plate to form the nozzle chamber ◆ Surface may be fragile to the touch	◆ Silverbrook, EP 0771 658 A2 and related patent applications ◆ IJ01, IJ02, IJ04, IJ11, IJ12, IJ17, IJ18, IJ20, IJ22, IJ24, IJ27, IJ28, IJ29, IJ30, IJ31, IJ32, IJ33, IJ34, IJ36, IJ37, IJ38, IJ39, IJ40, IJ41, IJ42, IJ43, IJ44

NOZZLE PLATE CONSTRUCTION				
	Description	**Advantages**	**Disadvantages**	**Examples**
Monolithic, etched through substrate	The nozzle plate is a buried etch stop in the wafer. Nozzle chambers are etched in the front of the wafer, and the wafer is thinned from the back side. Nozzles are then etched in the etch stop layer.	◆ High accuracy (<1 μm) ◆ Monolithic ◆ Low cost ◆ No differential expansion	◆ Requires long etch times ◆ Requires a support wafer	◆ IJ03, IJ05, IJ06, IJ07, IJ08, IJ09, IJ10, IJ13, IJ14, IJ15, IJ16, IJ19, IJ21, IJ23, IJ25, IJ26
No nozzle plate	Various methods have been tried to eliminate the nozzles entirely, to prevent nozzle clogging. These include thermal bubble mechanisms and acoustic lens mechanisms	◆ No nozzles to become clogged	◆ Difficult to control drop position accurately ◆ Crosstalk problems	◆ Ricoh 1995 Sekiya et al USP 5,412,413 ◆ 1993 Hadimioglu et al EUP 550,192 ◆ 1993 Elrod et al EUP 572,220
Trough	Each drop ejector has a trough through which a paddle moves. There is no nozzle plate.	◆ Reduced manufacturing complexity ◆ Monolithic	◆ Drop firing direction is sensitive to wicking.	◆ IJ35
Nozzle slit instead of individual nozzles	The elimination of nozzle holes and replacement by a slit encompassing many actuator positions reduces nozzle clogging, but increases crosstalk due to ink surface waves	◆ No nozzles to become clogged	◆ Difficult to control drop position accurately ◆ Crosstalk problems	◆ 1989 Saito et al USP 4,799,068

DROP EJECTION DIRECTION				
	Description	**Advantages**	**Disadvantages**	**Examples**
Edge ('edge shooter')	Ink flow is along the surface of the chip, and ink drops are ejected from the chip edge.	◆ Simple construction ◆ No silicon etching required ◆ Good heat sinking via substrate ◆ Mechanically strong ◆ Ease of chip handing	◆ Nozzles limited to edge ◆ High resolution is difficult ◆ Fast color printing requires one print head per color	◆ Canon Bubblejet 1979 Endo et al GB patent 2,007,162 ◆ Xerox heater-in-pit 1990 Hawkins et al USP 4,899,181 ◆ Tone-jet

DROP EJECTION DIRECTION				
	Description	**Advantages**	**Disadvantages**	**Examples**
Surface ('roof shooter')	Ink flow is along the surface of the chip, and ink drops are ejected from the chip surface, normal to the plane of the chip.	◆ No bulk silicon etching required ◆ Silicon can make an effective heat sink ◆ Mechanical strength	◆ Maximum ink flow is severely restricted	◆ Hewlett-Packard TIJ 1982 Vaught et al USP 4,490,728 ◆ IJ02, IJ11, IJ12, IJ20, IJ22
Through chip, forward ('up shooter')	Ink flow is through the chip, and ink drops are ejected from the front surface of the chip.	◆ High ink flow ◆ Suitable for pagewidth print heads ◆ High nozzle packing density therefore low manufacturing cost	◆ Requires bulk silicon etching	◆ Silverbrook, EP 0771 658 A2 and related patent applications ◆ IJ04, IJ17, IJ18, IJ24, IJ27-IJ45
Through chip, reverse ('down shooter')	Ink flow is through the chip, and ink drops are ejected from the rear surface of the chip.	◆ High ink flow ◆ Suitable for pagewidth print heads ◆ High nozzle packing density therefore low manufacturing cost	◆ Requires wafer thinning ◆ Requires special handling during manufacture	◆ IJ01, IJ03, IJ05, IJ06, IJ07, IJ08, IJ09, IJ10, IJ13, IJ14, IJ15, IJ16, IJ19, IJ21, IJ23, IJ25, IJ26
Through actuator	Ink flow is through the actuator, which is not fabricated as part of the same substrate as the drive transistors.	◆ Suitable for piezoelectric print heads	◆ Pagewidth print heads require several thousand connections to drive circuits ◆ Cannot be manufactured in standard CMOS fabs ◆ Complex assembly required	◆ Epson Stylus ◆ Tektronix hot melt piezoelectric ink jets

INK TYPE				
	Description	Advantages	Disadvantages	Examples
Aqueous, dye	Water based ink which typically contains: water, dye, surfactant, humectant, and biocide. Modern ink dyes have high water-fastness, light fastness	◆ Environmentally friendly ◆ No odor	◆ Slow drying ◆ Corrosive ◆ Bleeds on paper ◆ May strikethrough ◆ Cockles paper	◆ Most existing ink jets ◆ All IJ series ink jets ◆ Silverbrook, EP 0771 658 A2 and related patent applications
Aqueous, pigment	Water based ink which typically contains: water, pigment, surfactant, humectant, and biocide. Pigments have an advantage in reduced bleed, wicking and strikethrough.	◆ Environmentally friendly ◆ No odor ◆ Reduced bleed ◆ Reduced wicking ◆ Reduced strikethrough	◆ Slow drying ◆ Corrosive ◆ Pigment may clog nozzles ◆ Pigment may clog actuator mechanisms ◆ Cockles paper	◆ IJ02, IJ04, IJ21, IJ26, IJ27, IJ30 ◆ Silverbrook, EP 0771 658 A2 and related patent applications ◆ Piezoelectric ink-jets ◆ Thermal ink jets (with significant restrictions)
Methyl Ethyl Ketone (MEK)	MEK is a highly volatile solvent used for industrial printing on difficult surfaces such as aluminum cans.	◆ Very fast drying ◆ Prints on various substrates such as metals and plastics	◆ Odorous ◆ Flammable	◆ All IJ series ink jets
Alcohol (ethanol, 2-butanol, and others)	Alcohol based inks can be used where the printer must operate at temperatures below the freezing point of water. An example of this is in-camera consumer photographic printing.	◆ Fast drying ◆ Operates at sub-freezing temperatures ◆ Reduced paper cockle ◆ Low cost	◆ Slight odor ◆ Flammable	◆ All IJ series ink jets
Phase change (hot melt)	The ink is solid at room temperature, and is melted in the print head before jetting. Hot melt inks are usually wax based, with a melting point around 80 °C. After jetting the ink freezes almost instantly upon contacting the print medium or a transfer roller.	◆ No drying time-ink instantly freezes on the print medium ◆ Almost any print medium can be used ◆ No paper cockle occurs ◆ No wicking occurs ◆ No bleed occurs ◆ No strikethrough occurs	◆ High viscosity ◆ Printed ink typically has a 'waxy' feel ◆ Printed pages may 'block' ◆ Ink temperature may be above the curie point of permanent magnets ◆ Ink heaters consume power ◆ Long warm-up time	◆ Tektronix hot melt piezoelectric ink jets ◆ 1989 Nowak USP 4,820,346 ◆ All IJ series ink jets

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INK TYPE				
	Description	**Advantages**	**Disadvantages**	**Examples**
Oil	Oil based inks are extensively used in offset printing. They have advantages in improved characteristics on paper (especially no wicking or cockle). Oil soluble dies and pigments are required.	◆ High solubility medium for some dyes ◆ Does not cockle paper ◆ Does not wick through paper	◆ High viscosity: this is a significant limitation for use in ink jets, which usually require a low viscosity. Some short chain and multi-branched oils have a sufficiently low viscosity. ◆ Slow drying	◆ All IJ series ink jets
Micro-emulsion	A microemulsion is a stable, self forming emulsion of oil, water, and surfactant. The characteristic drop size is less than 100 nm, and is determined by the preferred curvature of the surfactant.	◆ Stops ink bleed ◆ High dye solubility ◆ Water, oil, and amphiphilic soluble dies can be used ◆ Can stabilize pigment suspensions	◆ Viscosity higher than water ◆ Cost is slightly higher than water based ink ◆ High surfactant concentration required (around 5%)	◆ All IJ series ink jets